

Status of the e-Ring Design for EIC *

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Abstract. The layout and main parameters of the e-ring for EIC project are presented. Optics properties to fulfil so-called spin-transparency conditions to obtain sufficient polarization degree at IP are given. The possibility of using super-bend magnets for polarization time in a wide energy range to decrease is also discussed.

INTRODUCTION

In the Brookhaven National Laboratory (BNL) experiments at new collider RHIC have successfully started with both ion-ion and polarized proton-proton beams [1]. To enhance the experimental capability of the RHIC complex, different schemes of $e-p$ collisions arrangement are under discussion at few last years. High luminosity polarized $e-p$ scattering will open unique opportunity for physics beyond limits of today experiments in polarized DIS.

This paper presents a study of the ring-ring option of EIC. A project of the electron ring with the energy 5–10 GeV was developed in collaboration between BINP (Novosibirsk), BATES-MIT Laboratory and BNL. We suggest (see the Fig. 1) to construct mainly outside the RHIC tunnel the electron storage ring which will have the circumference $\frac{4}{15}$ of the RHIC orbit and an intersection with ions in the one of the existing RHIC experimental area (on 12 o'clock).

The radiative polarization of the electron beam and a combination of solenoids and bending magnets will provide high degree of the longitudinal polarization of the electron beam in the IP. To minimize the reconstruction of the RHIC rings while adding the new electron ring two possible schemes of the interaction region arrangement are proposed: so-called horizontal "dog-leg" scheme and vertical one. Spin-transparency conditions which are needed for obtaining sufficient polarization degree in electron beam have been found for both options of the IP layout.

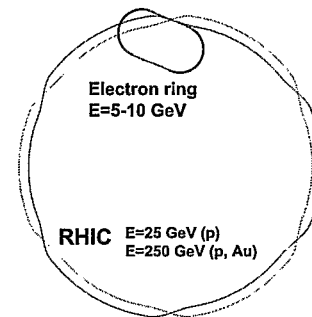


FIGURE 1. The general layout of the e-ring installed into the RHIC complex.

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THE LUMINOSITY CONSIDERATION

Achieving the high luminosity value of $1 \times 10^{33} \text{ cm}^2\text{s}^{-1}$ is a main challenge and needs a special consideration that has to take into account both a world wide experience of many machines, either electron's and proton's, and results of beam-beam interaction simulations. In particular, the simulations predict a number of advantages for round beam geometry by the collision due to a conservation of the angular momentum [2]. To satisfy the last requirement we should meet 2 conditions: equal beam sizes and equal tunes of betatron oscillations. Since origins of a forming of the beam emittances ($\varepsilon_e, \varepsilon_i$) are quite different, so as their dependences on the energy, lattices of the electron and ion rings have to provide some flexibility to control β^* -functions in the IP. In favour of the round beams the HERA and SPS experiences witness a bad life time and high background for unmatched beam sizes even with moderate beam currents.

The round beam luminosity is given by the equation:

$$L = F_{coll} \left(\frac{4\pi\gamma_e\gamma_i}{r_e r_i} \right) \cdot \xi_e \cdot \xi_i \cdot \sqrt{\frac{\varepsilon_e}{\beta_e^*} \cdot \frac{\varepsilon_i}{\beta_i^*}}, \quad (1)$$

where F_{coll} is the collision repetition frequency, γ and r are the relativistic factors and classical radii for electrons and ions correspondingly. Assuming the matched beam sizes, the space charge parameters ξ_e and ξ_i for electrons and ions are determined by the expressions:

$$\xi_e = \frac{N_i r_e Z}{4\pi\gamma_e \varepsilon_e}; \quad \xi_i = \frac{N_e r_i}{4\pi\gamma_i V_i \varepsilon_i Z}, \quad (2)$$

where N_e and N_i are electron and ion bunch populations; V_i is the ions velocity ($c=1$). The world wide experience shows that achievable values of the space charge parameters due to the beam-beam effects do not exceed 0.05 for electrons and 0.005 for protons.

Collision frequency F_{coll} is determined in our case practically by the ion bunch spacing in the RHIC. For realistic case of 360 ion bunches at RHIC, $F_{coll} = 28 \text{ MHz}$. Single bunch populations N_e and N_i are limited except the beam-beam interaction by different kinds of instabilities. For electrons the most severe intensity threshold is set by the head-tail transverse mode-coupling instability, that limits the one bunch population. The modern accelerator experience (for instance, in both B-factories or LEP collider), tells us, that $N_e = 1 \cdot 10^{11}$ is more or less a safe number. The proton bunch population is admitted to $N_p = 1 \cdot 10^{11}$, which is based on BNL and FNAL experimental results. To achieve the luminosity of $L = 1 \cdot 10^{33} \text{ cm}^2\text{s}^{-1}$ the beam size at the IP should be $\sigma_e^* = \sigma_p^* = 48 \mu\text{m}$ together with the other fixed above parameters.

RADIATIVE POLARIZATION AND E-RING DESIGN

The radiative polarization have been observed at the many electron storage rings. According this experience the energy range 5–10 GeV is quite comfortable for the obtaining the polarization degree about 80 percents. If the equilibrium polarization direction (vector \mathbf{n}) is vertical in the arcs we can expect a relatively low polarization losses caused by spin manipulations around the IP.

A radiative polarization time strongly depends on the bending field ($\tau_p \sim B^{-3}$). On the other hand the high magnetic field increases the energy losses for the synchrotron radiation ($\Delta E_{turn} \sim B^2$). A possible compromise here may be a special design of the bending magnets. We propose to use so-called super-bends magnets with relatively high field in a short central part of each magnet. It allows us strongly decrease the polarization time at low energies and suppress spin resonances by the relatively minimal energy losses. The possible optimum is to use high field in the super-bends at low energy (so to keep the polarization time at the level of 15 minutes at 5 GeV) and the uniform field at 10 GeV. But a final strategy of using the super-bends can be found during practical work with the beam polarization.

We considered the e-ring which consists of two arcs with regular FODO structure and two straight sections: one for the beams collisions and other for a technical usage. To deliver spin longitudinal into the IP we need to install two spin rotators on both sides of the interaction area. At first, spin is rotated by a solenoidal field to horizontal plane and then by low field dipoles (including final focus quadrupole magnets) exactly to the longitudinal direction at the medium energy 7.5 GeV.

The $\pm 90^\circ$ spin rotator consists of two super-conducting solenoids, each 3 m long, and with the field of about 6 T. Between solenoids a focusing structure is placed, which cancels the betatron coupling and minimizes negative effects from a spin perturbation w for momentum-off particles. The last requirement is so called spin transparency condition, which should be satisfied by the insertion optics, namely, the integral of the perturbation through the insertion azimuth θ should be made zero:

$$I = \int_{\theta_1}^{\theta_2} \mathbf{w} \eta d\theta = 0 \quad (3)$$

Here $\eta = \eta_1 - i\eta_2$ is a complex vector, which is composed from the unity vectors η_1 and η_2 , which in turn are the two orthogonal to the vector \mathbf{n} solutions of the spin motion equation for the equilibrium particle [3].

The spin perturbation components are [3, 4]:

$$w_x = v_0 z'' + K_x \frac{\Delta\gamma}{\gamma}; \quad w_z = -v_0 x'' + K_z \frac{\Delta\gamma}{\gamma}; \quad w_y = K_y \frac{\Delta\gamma}{\gamma}, \quad (4)$$

where $v_0 = \gamma a$ is the dimensionless spin tune, z'' and x'' are the second derivatives of the vertical or horizontal displacements over the azimuth θ ; $K_{x,y,z}$ are respectively the normalized horizontal, longitudinal or vertical magnetic fields.

We found a scheme of the focusing structure, that contains only regular quadrupoles inside the solenoid insertions and cancels the betatron coupling as well as creates the spin transparency. Transfer matrices of the whole insertion:

$$T_x = \begin{pmatrix} 0 & -2r \\ (2r)^{-1} & 0 \end{pmatrix} \quad T_z = \begin{pmatrix} 0 & 2r \\ -(2r)^{-1} & 0 \end{pmatrix} \quad (5)$$

Here r is a curvature radius in the solenoidal field B_y : $r = B\rho/B_y$,

The solenoids are located in the drift spaces, where the velocity vector \mathbf{v} has an angle $\pm 7.55^\circ$ with respect to the collision axis. After the solenoids spin precess around the vertical magnetic field (in case of horizontal "dog-leg" scheme) or around the horizontal magnetic field (in case of vertical "dog-leg" scheme), becoming at the medium energy 7.5 GeV purely longitudinal at the IP. On the opposite side of the interaction straight, spin is restored to vertical direction by the mirror symmetrical spin rotator. As a result, due to this antisymmetry and the spin transparency of the solenoidal rotators, the spin phase advance along the whole interaction region is zero, spin is always restored to the vertical direction in the next arc at arbitrary energy and the polarization behavior is mainly the same as without the spin rotators.

TABLE 1. General parameters of the eRHIC

Parameter	e-ring	p-ring
Circumference, m	1022	3833
Energy, GeV	5–10	250
Number of bunches	96	360
Bunch population	$1 \cdot 10^{11}$	$1 \cdot 10^{11}$
Beam current, A	0.45	0.45
RMS emittance, mm μ rad	45–63	9–13
Beta function at IP, cm	10	50
Beam size at IP, mm	0.07–0.08	0.07–0.08
Beam-beam parameter	≤ 0.05	≤ 0.005
Luminosity, cm $^{-2}$ s $^{-1}$	$(0.3 - 0.5) \cdot 10^{33}$	

The main parameters of the eRHIC for the current variants of electron and proton ring lattices are listed in the Table 1.

The reoptimization of the electron ring lattice, in order to produce smaller electron beam emittance, and the decrease of β^* value in the proton ring should provide the luminosity increase up to $1 \cdot 10^{33}$ level, as indicated by preliminary studies.

THE DETECTOR AREA LAYOUT

Besides the spin manipulations there are other issues for the IR design: beam separation to avoid the parasitic beam-beam interactions; focusing to the low beta; detector background; protection from the synchrotron radiation, etc. Both suggested schemes have transverse fields around the IP, that additionally to the spin rotation will separate the beams due to their big energy difference. The same fields could be used for a detector momentum analysis. In the case of longitudinal field in the detector compensating solenoids are needed to keep the zero spin rotation along the IR.

The first option supposes the lift up (about 1 m) one of the RHIC ion ring for the zero angle intersection with the flat electron ring. The Fig. 2 (left) shows schematically the interaction region (IR) and the spin vector behavior. Since the vector \mathbf{n} is lying in the horizontal plane between the two solenoidal spin rotators, some depolarization comes from the bending magnets in this area. A choice of moderate field magnitudes (few KGauss) helps to avoid substantial polarization losses. Calculations with the ASPIRRIN code [5] give the equilibrium polarization degree about 90% and the polarization time about 500 s at 10 GeV (see the Fig. 3).

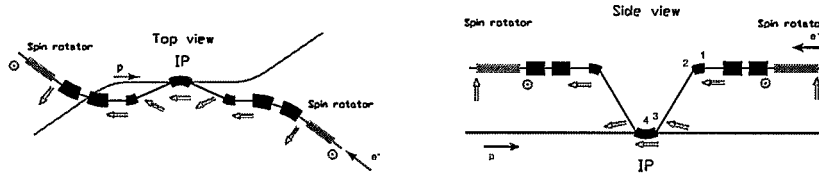


FIGURE 2. The layout of the e-ring interaction region.

One can see this scheme looks well for the electron polarization, but it might require serious rebuilding in the RHIC machine. That's why we considered other scheme with flat ion ring and a vertical orbit bump (about 0.5 m) in the electron ring, see the Fig. 2 (right).

In this variant the proton ring of the RHIC is almost unchanged except a new final focusing to get the low beta. The vertical profile of the e-ring have to be done also with the respect to the spin transparency, that in this case leads to demands on the betatron trajectory slopes at fixed points from 1 to 4:

$$z'_4 - z'_1 = 0; \quad x'_3 - x'_2 = 0. \quad (6)$$

As the polarization calculations by ASPIRRIN shown, despite of the spin transparency, the vertical bend initiates some spin resonances even in the ring without any imperfections (the Fig. 3). The situation is dramatically changed due to random vertical fluctuations of the arc quadrupoles positioning. The polarization does not exceed 50 percents with the RMS shift 0.5 mm.

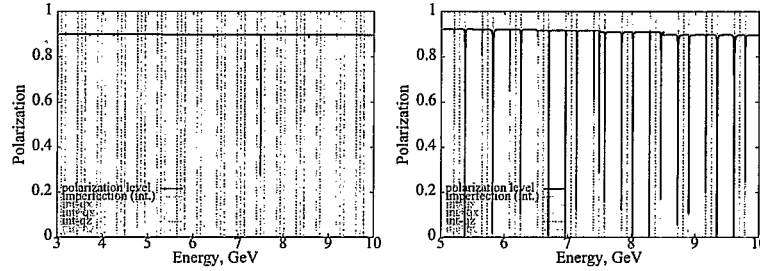


FIGURE 3. The equilibrium polarization vs. the energy in e-ring: left — horizontal dog-leg scheme, right — vertical dog-leg scheme. Intrinsic and imperfection resonances are also shown.

CONCLUSION

The present study shown that the ring-ring option of the electron-proton collider is able to provide the luminosity up to $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ in the SCM energy range 15-100 GeV. The project of the electron ring with the super bend magnets and the solenoidal spin rotators performs to obtain not less 70 percents of the longitudinal polarization in the IP.

Two possible layouts of the interaction region are considered. The scheme with flat electron ring (horizontal "dog leg") looks preferable for the electron polarization. A serious consideration of a new RHIC final focus design for the low beta is needed.

There are a number of topics which have not been mentioned in this paper: a flexible arcs lattice to control the electron beam emittance, chromaticity corrections, dynamical aperture, required cooling of ion beam, etc. That have to be subjects of further investigations.

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